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IDENTIFYING THE MYSTERIOUS EGRET SOURCES: SIGNATURES OF POLAR CAP PULSAR MODELS

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Abstract The advent of the next generation of gamma-ray experiments, led by GLAST, AGILE, INTEGRAL and a host of atmospheric Čerenkov telescopes coming on line in the next few years, will enable ground-breaking discoveries relating to the presently enigmatic set of EGRET/CGRO UID galactic sources that have yet to find definitive identifications. Pulsars are principal candidates for such sources, and many are expected to be detected by GLAST, some that are radio-selected, like most of the present EGRET/Comptel pulsars, and perhaps even more that are detected via independent pulsation searches. At this juncture, it is salient to outline the principal predictions of pulsar models that might aid identification of gamma-ray sources, and moreover propel subsequent interpretation of their properties. This review summarizes relevant characteristics of the polar cap model, emphasizing where possible distinctions from the competing outer gap model. Foremost among these considerations are the hard X-ray to gamma-ray spectral shape, high energy cutoffs and pulse profiles, and how these characteristics generally depend on pulsar period and period derivative, as well as observational viewing angle. The polar cap model exhibits definitive signatures that will be readily tested by the detections of GLAST and other experiments, thereby establishing cogent observational diagnostics. The paper focuses on different classes of pulsars that might define agendas and parameter regimes for blind gamma-ray pulsation searches; examples include the highly-magnetized ones that are currently quite topical in astrophysics.

1. INTRODUCTION

Pulsars are a central part of any discussion of candidates for the putatively galactic population of EGRET unidentified (UID) sources. A major factor in this is their inherent nature in being both among the brightest galactic sources (for observational summaries, see Kanbach, these proceedings, Thompson 2001), and moreover being distinctive via their pulsations. These features have fed the historical evolution of the field of unidentified gamma-ray sources, with pulsars leading the *post-facto* galactic identifications (e.g. see Thompson, these proceedings). There is a pervasive feeling in the gamma-ray community, as embodied in the course of this Workshop, that such a situation will persist. This perception is driven by the expectation that the Gamma-Ray Large Area Space Telescope (GLAST: <http://www-glast.stanford.edu>) will detect pulsars in profusion, some that are radio-selected, like most of the present EGRET/Comptel pulsars, and perhaps even more that are detected via independent (blind: i.e. not radio or X-ray selected) pulsation searches. Current estimates of the anticipated GLAST pool of pulsars range from dozens to several hundred (e.g. Harding, 2001b), depending on whether an outer gap or polar cap model is preferred, and on specific assumptions pertaining to each model. This population should account for a significant fraction of the present EGRET UID galactic sources. Furthermore, it should provide an ample dataset for exploring pulsar physics in general, and enable discrimination between the outer gap and polar cap scenarios in particular.

Discussions of the generic features of each leading model for gamma-ray emission in pulsars are therefore timely. The outer gap (OG) case, where the accelerating potential is far removed from the stellar surface and more proximate to the light cylinder, is advocated by Romani (these proceedings). This paper presents the perspective of the polar cap (PC) model, where particle acceleration is effected either just above or within a stellar radius or two of the neutron star surface, and is presumed to occur on the open field lines near the polar cap (e.g. Sturrock 1971; Ruderman & Sutherland 1975; Arons & Scharlemann 1979; see also the recent review by Harding 2001a). Motivations for preferring a polar cap scenario include, but are not limited to, (i) a difficulty in accepting a viewpoint that electrodynamic dissipation near the stellar surface is only a minor contributor to the pulsar's high energy radiative signals, (ii) the connection of gamma-rays to coherent radio emission in PC models, mediated by single photon pair creation in strong magnetic fields, (iii) the relatively narrow range of ages permitted for gamma-ray pulsars according to the outer gap model, (iv) the fact that the polar cap

prediction (Harding 1981) of pulsar luminosity scaling approximately with open line field voltage was confirmed by the EGRET/Comptel pulsar collection (e.g. see Fig. 4 of Thompson 2001, for the status quo of this correlation), and (v) the predictions (Cheng, Ho & Ruderman 1986; Cheng 1994; Yadigaroglu & Romani 1995; Romani 1996) from earlier inceptions of outer gap models of many radio-quiet gamma-ray pulsars and also inverse Compton emission at TeV energies, forecasts that have not been borne out by subsequent observations. While the first two of these are largely conceptual preferences, the last two connect to reality. Geminga stands alone is the only potentially radio-quiet “garden-variety” gamma-ray pulsar, and the constraining limits to TeV (pulsed) emission from pulsars obtained by Atmospheric Čerenkov Telescopes (e.g. Nel et al. 1993; Lessard et al. 2000) have forced the revision (e.g. Hirotani, 2000) of TeV flux estimates from outer gap models.

The features of the polar cap model are intimately connected to the extremely strong magnetic field that threads the emission region. It is this field that controls the maximum energy of emission, the nature of pair creation, and a host of physics that determines the pulsar spectrum and influences the pulse shape. This review will highlight some of these properties, and explore how (mostly) spectral and temporal characteristics generally depend on pulsar period and period derivative, as well as on observational viewing angle. The polar cap model exhibits definitive signatures that will be readily tested by the detections of GLAST and other experiments, thereby establishing palpable observational diagnostics. Discerning which of the outer gap and polar cap models is most appropriate for gamma-ray pulsars, or whether each has its own domain of applicability, is a central quest for pulsar astrophysicists. While preparatory analysis for the GLAST era is a worthwhile goal alone, perhaps most salient for the subject of this meeting is a definition of identification strategies for gamma-ray sources, based on the global characteristics of pulsar models and the assumption that pulsars constitute a sizeable fraction of the EGRET UID collection; this will form the focus at the end of this review.

2. POLAR CAP MODELS OF GAMMA-RAY PULSARS

The polar cap scenario is attractive from a physics perspective. Nevertheless, like its outer gap competitor, it remains unproven. Hence it is imperative to establish definitive/unambiguous properties and predictions that enable a determination of its applicability to gamma-ray pulsars. This can be achieved via two approaches. The first is to isolate

individual pulsars for analysis, and explore the model behavior of phase-resolved spectra (and also polarization swing profiles in an ideal world where gamma-ray polarimetry is accessible: see Section 3) that can be compared to high quality temporal and spectral data. This has been the approach of Daugherty & Harding (1996), Dyks & Rudak (2000) and Romani (1996) using the Vela pulsar as a test case in supporting their competing perspectives. The major drawback of such isolated focuses is that the models have enough parameters to render model discrimination near impossible. Therefore, multiple objects need to be considered, a time-consuming task for pulsar-by-pulsar analyses. This leads to the second diagnostics method: population statistics. It is expedient to identify global characteristics of the models so as to define parametric trends that can be confirmed or disproven given a large database such as that to be afforded by GLAST. Given the disparity in emission region geometry and operable physics incorporated in the polar cap and outer gap scenarios, it is improbable that they will provide a collection of similar or coincident behavioral trends. Hence, the emphasis of this paper will be to address the more global signatures of polar cap models by first defining the relevant cascade and radiative properties.

Basic Properties of Cascades. Polar cap models for pulsar high-energy emission are generally based on the idea, dating from the earliest pulsar models of Sturrock (1971) and Ruderman & Sutherland (1975; hereafter RS75), of particle acceleration and radiation near the neutron star surface at the magnetic poles. Within this broad class, there is a large variation, with the primary division being whether or not there is free emission of particles from the neutron star surface. This question hinges on whether the surface temperature T of the neutron star (many of which have now been measured in the range $T \sim 10^5 - 10^6$ K; Becker & Trümper 1997) exceeds the ion, T_i and electron, T_e , thermal emission temperatures. If $T < T_i$, a vacuum gap will develop at the surface, due to the trapping of ions in the neutron star crust (RS75, Usov & Melrose 1995). In this case, the particle acceleration and radiation will take place very near the neutron star surface. If $T > T_e$, free emission of particles of either sign of charge will occur. The flow of particles is then limited only by space charge, and an accelerating potential will develop (Arons & Scharlemann 1979; Muslimov & Tsygan 1992) due to an inability of the particle flow all along each open field line to supply the corotation charge that is required to short out the electric field component E_{\parallel} along the magnetic field lines. In space charge-limited flow models, the accelerating E_{\parallel} is screened at a height where the particles radiate γ -

rays that produce pairs. This so-called pair formation front (e.g. Arons 1983, Harding & Muslimov 1998) can occur at high altitudes above the polar cap, a property that may prove necessary to explain the spectral cutoffs in the some or most of the EGRET pulsars.

The acceleration of primary electrons is rapid and ceases when one of two types of radiative cooling becomes significant. This establishes the maximum Lorentz factor γ_e of these particles, and a quasi-monenergetic primary distribution is established prior to cascading. The two cooling mechanisms are curvature radiation induced by the magnetic field line curvature, the process that is more widely cited in pulsar literature as a primary emission mechanism, and resonant (magnetic) inverse Compton scattering of thermal X-rays from the stellar surface (e.g. Sturmer and Dermer 1994), a relatively recent consideration. Both are strong functions of the magnetic field strength and either the electron's Lorentz factor or the field geometry. Curvature radiation-initiated cascades generally have $\gamma_e \sim 10^7$ (e.g. Daugherty & Harding 1989; see also Harding & Muslimov 1998), while inverse-Compton seeded pair cascades yield $\gamma_e \sim 3 \times 10^5 - 10^6$ (e.g. Sturmer 1995; see also Harding & Muslimov 1998). Such photons propagate through the magnetosphere until they achieve sufficient angles θ_{kB} with respect to the magnetic field to permit the creation of pairs via $\gamma \rightarrow e^+e^-$ above the threshold energy of $2m_e c^2 / \sin \theta_{kB}$. This propagation is influenced by general relativistic distortions of photon trajectories and field structure (e.g. Gonthier & Harding 1994; Harding, Baring & Gonthier 1997), as is the magnitude of the field in the local inertial frame. For small polar cap sizes, corresponding to longer pulsar periods, it is the failure of the primary photons to acquire sufficient angles θ_{kB} at low to moderate altitudes (prior to dipole field decline) that is primarily responsible for the existence of a theoretical death line for radio pulsars (Sturrock, Baker & Turk 1976): pair creation is quenched at high altitudes since the rate is a strongly increasing function of \mathbf{B} (e.g. Tsai & Erber, 1974).

The first generation of pair creation initiates the pair cascade, with pairs generally being created in excited transverse (to the field) momentum states, the so-called Landau levels. De-excitation via cyclotron and synchrotron radiation is then extremely rapid, on timescales of 10^{-16} sec or less for typical neutron star fields of $B_0 \gtrsim 10^{12}$ Gauss (n.b. subscripts zero denote polar surface fields). These secondary photons can then travel to higher altitudes and create further pairs and successive generations of photons. So proceeds the cascade, with a typical number of generations being around 3–4, and the total number of pairs per primary electron being of the order of $10^3 - 10^4$ (Daugherty & Harding 1982). The cumulative product is an emission spectrum that comprises

a curvature/inverse Compton continuum that is cut off at hard gamma-ray energies by pair creation, with the addition of several synchrotron components at successively lower energies, terminating when the magnetosphere becomes transparent to $\gamma \rightarrow e^+e^-$ at significant altitudes. The details of such spectral formation are discussed below. A notable exception to this cascade scenario arises in highly-magnetized pulsars, PSR 1509-58 (with $B_0 \sim 3 \times 10^{13}$ Gauss) being the case in point. When the surface polar field B_0 exceeds around 6×10^{12} Gauss, pairs are produced in the zeroth (ground state) Landau level (Baring & Harding 2001, hereafter BH01), so that cyclotron/synchrotron emission is prohibited. Cascading is then effectively squelched and the pair yield diminished (BH01). A possible amelioration of this circumstance was posited by Zhang & Harding (2000a), namely the Landau level excitation of higher generation pairs via Compton scatterings with X-rays from the surface. Since such excitation can only arise above the cyclotron resonance (e.g. Gonthier et al. 2000), Baring & Harding (2001) determined that the population of excited Landau states relative to that in the ground state is small.

A more fascinating variation on the cascade theme involves the phenomenon of photon splitting, again applicable to high field pulsars. Magnetic photon splitting, $\gamma \rightarrow \gamma\gamma$, a third-order (in the fine structure constant $e^2/\hbar c$) quantum electrodynamical (QED) process in which a single photon splits into two lower-energy photons (Adler 1971, Baring & Harding 1997), operates efficiently and competes effectively with pulsar pair production only in magnetic fields above $\sim 10^{13}$ Gauss (Harding, Baring & Gonthier 1997, hereafter HBG97). This region of high magnetic field strength lies in the upper-right part of the $P - \dot{P}$ diagram. Splitting is forbidden in field-free regions by Furry's theorem, a symmetry property of QED. In regimes of weak or modest fields when vacuum dispersion effects are small, $\gamma \rightarrow \gamma\gamma$ is a collinear process, conserving both energy and momentum. The rate of splitting, like that of magnetic pair creation $\gamma \rightarrow e^+e^-$, is generally a rapidly increasing function of field strength (the exception being at fields $B \gtrsim 10^{14}$ Gauss), photon energy and photon propagation angle with respect to the field. However, splitting possesses no energy threshold, so that it can and does dominate the first order process of pair creation if \mathbf{B} is sufficiently high. This leads to an alternative channel for cascade cessation, with gamma-rays being reprocessed without yielding pairs so that synchrotron generations are suppressed. The result is distinctive bumps and polarization signals in the EGRET/Comptel band (HBG97). The issue of splitting-influenced pulsar cascades is addressed below in Section 3 and in depth in HBG97 and Baring & Harding (2001).

3. PREDICTIONS OF POLAR CAP MODELS

Having assembled the basic ingredients of pulsar cascades, the task here is to identify the array of radiative signatures that are the hallmark of polar cap models. Since the cascade physics differs according to the period P and period-derivative \dot{P} of the pulsar, for the purposes of this discussion a division is made between the canonical Crab-like/Vela-like young pulsars with moderately strong fields, and their more highly-magnetized cousins like PSR 1509-58. The focus in this section is mainly on pulsars whose beam sweeps across the line of sight to Earth, so-called *on-beam* pulsars; off-beam pulsars will also be mentioned briefly.

Crab-like and Vela-like pulsars. Here we consider “standard” bright young pulsars like the Crab, Vela and Geminga with moderately high, but not extremely high, surface polar fields B_0 . These constitute the majority of EGRET/Comptel pulsars, with PSR 1509-58 (addressed in the next subsection) and the millisecond pulsar PSR J0218+4232 (Kuiper et al. 2000) being the notable exceptions. Spectral properties will be the first focus. From the discussion of cascade properties above, this case corresponds to synchrotron-curvature cascades if the pulsar period is substantially shorter than a second. The curvature spectrum is generated by a quasi-monoenergetic electron injection that results from the rapid electrodynamic acceleration. Since the curvature mechanism is essentially identical to the synchrotron one, except that the relevant curvature scale is the radius of field curvature as opposed to the gyro-radius, simple synchrotron formalism can be applied (e.g. see Jackson 1975) to yield a spectrum of $\varepsilon^{-2/3}$ below a maximum cutoff energy. This result holds provided that there is no cooling during emission, which is generally not the case. With curvature cooling operating (i.e. when $P \lesssim 0.3$ sec), the spectrum steepens to $\varepsilon^{-5/3}$ (e.g. Daugherty & Harding 1982), a power-law that extends down to energies at which cooling becomes inefficient, and then the flat $\varepsilon^{-2/3}$ form is again assumed.

Superposed on this are contributions from synchrotron emission from successive generations. Since these components result from pairs that are created by the photon spectrum belonging to a previous cascade generation, and the pair injection traces the input photon spectrum, it is straightforward (e.g. Wei, Song & Lu 1997; Harding & Daugherty 1998; Baring & Harding 2000) to determine that the spectral index α_i of the i^{th} generation (i.e. for $dn_\gamma^{(i)}(\varepsilon)/d\varepsilon \propto \varepsilon^{-\alpha_i}$) satisfies the recurrence relation $\alpha_{i+1} = (\alpha_i + 1)/2$. This result assumes that synchrotron cooling of the pairs rapidly depopulates excited Landau levels and steepens the pair spectrum by an index of unity. It then follows that (Harding &

Daugherty 1998)

$$\alpha_n = 2 - \frac{2 - \alpha_1}{2^{n-1}} \quad , \quad (1.1)$$

where the primary index is $\alpha_1 \approx 5/3$. Hence, each generation steepens in spectral index, so that, due to its preponderance of photons, the last generation determines the emergent cascade index. Notice that the asymptotic index for a large number of generations is 2. This automatically creates difficulties within this framework for pulsars with spectra steeper than ε^{-2} , the Crab being the notable case. However, it must be remembered that such simple analytic determinations are “one-zone” computations, and that the cascade spans a range of altitudes and field geometries, all of which modify this picture of steepening. In particular, the finite generational energy degradation $\chi = 0.5 \max[B/B_{\text{cr}}, 0.1]$ (i.e. such that photon energies satisfy the recurrence relation $\varepsilon_{i+1} \sim \chi \varepsilon_i$) disrupts the idealized picture of power-laws generating power-laws, since the structure introduced by pair creation cutoffs (discussed below) influences successive generations to introduce additional steepening. Note that, hereafter, $B_{\text{cr}} = 4.413 \times 10^{13}$ G denotes the quantum critical field.

The spectral index is not a free parameter, but is determined roughly by noting that cascade cessation occurs when the mean free path for pair creation is comparable to the stellar radius R_0 , i.e. the scalelength for field decline. This then establishes (e.g. Harding, private communication; Baring & Harding 2000) the effective maximum number of cascade generations (permitted to be a non-integer, following Lu, Wei & Song 1994)

$$n = 2 + \frac{1}{\log_e \chi} \log_e \left[\frac{4}{3\pi} \frac{B_{\text{cr}}}{B_0 \gamma_1^3} \left(\frac{r}{R_0} \right)^4 \frac{P_c}{\lambda_c} \right] \quad (1.2)$$

for pulsar period P (in seconds) and electron primary Lorentz factor γ_1 . Here λ_c is the Compton wavelength over 2π . Observe the appearance of a local field $B_0(r/R_0)^{-3}$ factor. This relation provides a closed system, establishing the spectral index as a function of spin-down parameters P and B_0 and the (unknown) altitude $r - R_0$ of typical emission above the surface. Variations on this *generation index* formulation can be found in Lu, Wei & Song (1994) and Wei, Lu & Song (1997), and also in Zhang & Harding (2000a) who treat (resonant) inverse Compton cascading as well to probe spectral signatures in the X-ray band. While details of “altitudinal smearing” will muddy this spectral index determination (as is evident in the comparison of such predictions with EGRET pulsar characteristics in Harding & Daugherty 1998), one expects the overall global trends with B_0 and pulsar period to be approximately true for polar cap models, providing a powerful observational diagnostic. Gen-

erally, the number of generations and the spectral index are *increasing functions of B_0 , but decreasing functions of the altitude.*

It must be emphasized that the mean spectral index of EGRET UIDS that are associated with the Gould Belt is around 2.25 (Grenier et al. 2000; see also Gehrels et al. 2000), greater than that of most EGRET pulsars; resolution of this mismatch may be found in the discussion of off-beam pulsars below. A brief comment on the phase-dependence of spectra is also warranted, since pulse-phase spectroscopy is an objective of pulsar studies, attainable for a large number of pulsars in the GLAST era. Constraints on model phase space are narrowed considerably by exploration of the spectral variations with phase, though both polar cap (Daugherty & Harding 1996; Dyks & Rudak 2000) and outer gap (Roman 1996) models have successfully accounted for Vela's properties (see also Zhang & Cheng 2001 for an outer gap consideration of Geminga). A characteristic that has emerged in gamma-ray pulsars is that their trailing peak and interpulse spectra are flatter (e.g. Thompson 2001; see also Kanbach et al. 1994 for Vela details) than their leading peak spectra, features that need to be modelled. The interpulse emission is generally expected to be harder in the polar cap model, since there is less cascading near the pole (Daugherty & Harding 1996), and the spectrum possesses mostly primary curvature radiation. The range of altitudes probed is a function of geometrical perspective, and hence also of pulse phase. Given the number of free parameters in models, it is critical to survey an array of pulsars in model/data comparisons of spectral and temporal properties.

The next major spectral feature is the maximum energy of emission, which is controlled by attenuation due to pair creation during photon propagation through the pulsar magnetosphere. This attenuation leads to the reprocessing that spawns lower energy photons, and provides a characteristic super-exponential turnover (e.g. Daugherty & Harding 1996) that contrasts that expected in outer gap models (e.g. see Thompson 2001 for a comparison). $\gamma \rightarrow e^\pm$ occurs at the threshold $\varepsilon \sin \theta_{kB} = 2$ for $B \gtrsim 0.1B_{cr}$ and above threshold at $\varepsilon \sin \theta_{kB} \sim 0.2B_{cr}/B$ for lower fields (e.g. see Daugherty & Harding 1983). Here, θ_{kB} is the angle of photon propagation relative to \mathbf{B} , and hereafter photon energies ε are expressed in units of $m_e c^2$. Hence, the mean free path for photon attenuation in *curved* fields is $\lambda_{pp} \sim \rho_c/\varepsilon \max\{2, 0.2/B\}$, i.e. when $\varepsilon \sin \theta_{kB}$ crosses above threshold. The radius of field curvature is $\rho_c = [Prc/2\pi]^{1/2}$ for a pulsar period P . Pair creation cutoff energies ε_{MAX} , derived from the codes developed in HBG97 and Baring & Harding (2001), are plotted in Figure 1. While these are refined estimates, including the effects of general relativity on

spacetime curvature, field enhancement and photon energy, their empirical dependence on B_0 , R_0 and pulsar period P (in seconds) can be summarized in the relation (see also Harding, 2001a)

$$\varepsilon_{\text{MAX}} \approx 0.4\sqrt{P} \left(\frac{r}{R_0} \right)^{1/2} \max \left\{ 1, \frac{0.1 B_{\text{cr}}}{B_0} \left(\frac{r}{R_0} \right)^3 \right\} \text{GeV} . \quad (1.3)$$

Refinements to this estimate to include the effects of photon splitting in higher fields (near B_{cr}) are discussed in Baring & Harding (2001). The overall trend is clear: there is a strong anti-correlation between the maximum energy and the surface magnetic field, which seems to be augmented by an apparent decline of emission altitude with B_0 . Such a trend is a distinctive characteristic that can be probed by GLAST and is unlikely to be reproduced by outer gap models. Note also, that the maximum energy is generally in the 1–10 GeV band for normal young pulsars, can be much lower (e.g. HBG97, BH01) for highly magnetized ones, and also much higher for millisecond pulsars (Bulik, Rudak & Dyks 2000) so that sub TeV-band (i.e. ~ 50 –100 GeV) signals are possible for polar cap models via synchrotron/curvature cascades if the field is low enough. It also should be remarked that the cutoff energy depends on pulse phase, with slightly greater values achieved between the pulse peaks in the case of Vela modelling (Daugherty & Harding 1996); such a property matches the EGRET observations (Kanbach et al. 1994).

The other major spectral feature in the gamma-ray band corresponds to the lower energy of the cascade, which from Monte Carlo simulations (e.g. Daugherty & Harding 1982) corresponds to Lorentz factors γ_{MIN} of around 50–100 for Vela-like pulsars. The synchrotron photon energy for this Lorentz factor is $\varepsilon_{\text{MIN}} \sim \gamma_{\text{MIN}} B / B_{\text{cr}}$, noting that a factor of $1/\gamma_{\text{MIN}}$ is introduced to account for the cascade beaming. This energy is typically in soft gamma-rays, and generally γ_{MIN} depends on B_0 , P , etc. in more or less the same manner (Baring & Harding 2000) that ε_{MAX} does in Eq. (1.3), since the same pair creation physics applies to both. However, the reprocessing that leads to the establishment of ε_{MIN} occurs at lower altitudes (yielding possibly different parametric dependences) than the ultimate attenuation that defines ε_{MAX} , so that in general $\varepsilon_{\text{MIN}} \ll \varepsilon_{\text{MAX}}$; it is difficult to be more specific than this inequality. In addition, since there is probably little altitudinal dependence in ε_{MIN} , contrasting that for ε_{MAX} inferred from Figure 1, one might expect a spectral “narrowing” with increasing B_0 . The spectrum possesses a break at ε_{MIN} , below which it assumes the flat $\varepsilon^{-2/3}$ form that signifies curvature or synchrotron emission from quasi-monoenergetic pairs. Such a slope is consistent with the broad-band optical/ hard X-ray non-thermal continuum of the Vela pulsar that lies underneath the thermal

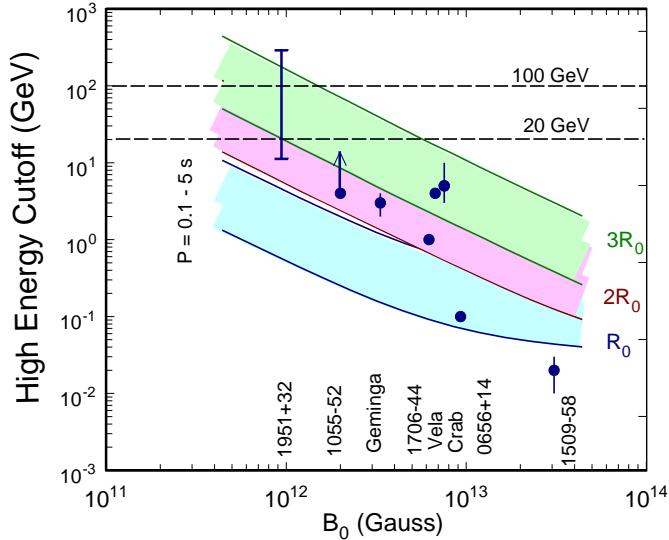


Figure 1 Maximum pulsar emission energies (from Baring & Harding 2000) imposed by pair creation attenuation at different altitudes, described empirically via Equation (1.3). For each altitude, a range of pulse periods (polar cap sizes) is represented by a shaded band. These energies are determined by the more involved photon propagation/attenuation code described in Baring & Harding (2001). Inferred cutoff energies (or ranges) for 8 gamma-ray pulsars of different B_0 are indicated, from which a trend of declining altitude of emission with increasing B_0 is suggested.

surface X-rays (e.g. see Pavlov et al. 2001 for a spectrum). Note that when the surface field becomes sufficiently high, the cyclotron scale imposes structure on the spectrum and redefines the variation of ε_{MIN} with B_0 ; this situation is sampled by the highly-magnetized pulsars.

PSR 1509-58 and high B pulsars. Having established the generic properties of the more familiar gamma-ray pulsars, it is salient to move on to their more highly-magnetized siblings. The operative cascade physics is identified in Section 2. High fields of pulsars like PSR 1509-58 inhibit cascading (BH01) via the suppression of pair creation. This removes the complexity of the sequence of synchrotron components and leaves a bare curvature (or inverse Compton) primary electron spectrum, which is generically flat. The spectral index of PSR 1509-58, roughly 1.6 (e.g. see HBG97), is consistent with curvature emission from cooled primaries. Accordingly, it can be deduced that increasing the surface field must at some point flatten the pulsar continuum. This starkly contrasts the inference from Eq. (1.1) of steepening with increasing B_0 ;

this trend reversal, probably at around $B_0 \sim 10^{13}$ Gauss, is a distinctive prediction of the polar cap model. Therefore, to address the focus of this paper, based on these spectral slope issues, it appears unlikely that *on-beam* high field pulsars are optimal candidates for EGRET UIDs, which appear to have spectra steeper on average than ϵ^{-2} , at least those correlated with the Gould Belt (Gehrels et al. 2000, Grenier et al. 2000; see also the reviews by Grenier and Gehrels in these proceedings). Note that the determination of UID spectral indices is subject to selection effects against detecting steep spectrum sources; this suggests that the true average may be even steeper.

This pessimism is reinforced by the expectation that high field pulsars have low maximum energies, according to the pair creation turnovers predicted and observed in Figure 1. This is dramatically emphasized by the lack of an EGRET detection for PSR 1509-58. Such an absence of emission is extremely constraining on spectral models, and was exploited by HBG97 to assert that photon splitting was acting in PSR 1509-58. Splitting attenuates photons at somewhat lower energies than does pair creation in such high B pulsars (see BH01 for details). This implies that the true ϵ_{MAX} curves in Figure 1 lie somewhat lower than the $\gamma \rightarrow e^\pm$ ones displayed at $B \gtrsim 10^{13}$ Gauss when $\gamma \rightarrow \gamma\gamma$ is taken into account. HBG97 observed that splitting naturally accounts (pair creation alone cannot, as is obvious from the figure) for the inferred turnover at around 10–30 MeV in PSR 1509-58 if a standard polar cap size is assumed and general relativity is incorporated in photon transport calculations. This study provided a nice piece of circumstantial evidence for the action of photon splitting, an interesting prospect for physics.

Returning to the EGRET UIDs, these opacity constraints indicate that high B sources can only be candidates if their emission regions are at relatively high altitudes, for which there is no confirmed observational evidence. Nevertheless, if the galactic UIDs turn out to be high B pulsars, they would then be expected to have steep spectra if the cutoff always matches the EGRET band, an improbable fine-tuning. The cut-offs would not be super-exponential, the signature of pair creation, but rather more gradual if splitting is operating. In such a case, there would be a segregation of flatter Crab-like and Vela-like pulsars in the galactic plane, and steep-spectrum higher field pulsars at low to moderate galactic latitudes. How such a correlation between B_0 and latitude (i.e. perhaps also kick velocity) would be attained is presently unclear.

Before closing this subsection it is desirable to make a small pitch for **gamma-ray polarimetry**. This is perhaps most relevant to high B pulsars, but is still quite important for the more common EGRET pulsars. Gamma-ray polarimetry is traditionally a haven for skeptics,

though the mood of the high energy astrophysics community is rapidly changing given the prospects (Lei, Dean & Hills, 1997) that the INTEGRAL mission will detect polarization at the 10% level from the Crab pulsar (at 200–600 keV), and also in a handful of other sources. Hard gamma-ray experiments like GLAST are generally not afforded the opportunity to act as polarimeters, being limited by multiple scattering in trackers above 300 MeV. Despite early estimates of GLAST's potential polarimetric capability (Yadigaroglu 1997), current design precludes a major focus on this observational goal. Medium energy gamma-ray experiments, on the other hand, are ideally suited to polarization studies (via their sampling of Compton scattering kinematics), and accordingly considerable emphasis has been placed in recent workshops on such new developments for next-generation advanced Compton telescopes (e.g. see Kanbach et al. 2000, and the Web pages for the MEGA [<http://www.gamma.mpe-garching.mpg.de/MEGA/mega.html>] and ACT [<http://gamma.nrl.navy.mil/ngram/>] consortia). Science motivations for polarimetry are obvious for pulsars. The presence of strong fields virtually guarantees a strong polarization signal in polar cap models, and when these couple with spectral structure and temporal information, particularly powerful observational diagnostics are achieved. This may be fruitful at the lower end of the cascade continuum in Vela-like objects, but it is an especially valuable tool for highly-magnetized pulsars since the attenuation cutoffs fall in the Comptel band, and should exhibit strong and distinctive polarization signatures. A concerted effort to realize the historically ambitious goal of gamma-ray polarimetry may yield dramatic science gains in the near future.

Magnetars: not relevant for UIDs? A natural step from these considerations of high field pulsars is to magnetars, specifically anomalous X-ray pulsars (AXPs) and soft gamma repeaters (SGRs). These can be quickly dismissed as potential candidates for EGRET UIDs unless we have been unlucky in the observational process. To date, identified emission from these sources does not exceed 1 MeV for the SGRs (e.g. see data for giant flares in Mazets et al. 1981 for the 5th March 1979 [SGR 0525-66] event, and Hurley et al 1999 for SGR 1900+14) and considerably less for AXPs. Moreover, their spectra are typically steep, at least in quiescent epochs, generally precluding detection in the EGRET band. The possible exceptions are the so-called “initial hard spikes” in the two cases of giant flares of SGR 0525-66 (in 1979) and SGR 1900+14 (in 1998), neither of which was seen by a hard gamma-ray mission. Hence, observationally there is still the possibility that this particular mode of activity may generate super-MeV emission, a question that GLAST

might be able to answer. From the theoretical viewpoint, high energy emission is not readily expected from these sources, if the magnetar interpretation is adopted. This is because the magnetospheric opacity due to pair creation and photon splitting will inhibit escape of photons above around 50–200 MeV (e.g. see Figure 9 of BH01). This bound applies specifically to a “pulsar mode,” where (e.g. giant flare) emission is strongly coupled to a beam near the polar cap; extending to equatorial regions enhances the opacity and can force the spectrum down into the hard X-ray/soft gamma-ray band (Baring 1995, Harding & Baring 1997), more commensurate with that seen in normal SGR outbursts and AXPs. The escape clause here is to reduce the strength of the ambient magnetic field, i.e. either to relinquish (untenable to some) the magnetar interpretation, or to move the giant flare emission region to higher altitudes (not necessarily outer gaps), a prospect that is difficult to reconcile with the enormous energy liberated in SGR giant flares.

Radio quiescence at high B ? An issue that impacts the discussion of unidentified gamma-ray sources is the existence or otherwise of radio counterparts. This concerns highly-magnetized pulsars, if they can be radio quiet without dramatically inhibiting gamma-ray emission, as has been suggested by Baring and Harding (1998, see also Zhang & Harding 2000b). Since it is commonly assumed (e.g. Sturrock 1971; Ruderman & Sutherland 1975; Arons & Scharlemann 1979; for a dissenting view, see Weatherall & Eilek 1997) that a plentiful supply of pairs is a prerequisite for coherent radio emission at observable flux levels, any suppression of pair creation in pulsars implies that the emission of radio waves should be strongly inhibited. Baring & Harding (1998) posited the idea that photon splitting could effect a suppression of pair creation by providing a more competitive mode of photon attenuation for high polar fields. Accordingly, they predicted an approximate boundary in the P - \dot{P} diagram that delineated pulsars of lower \dot{P} (or B_0) that could be radio-loud, and those of unusually large period derivative, which were necessarily radio quiet due to the action of splitting. The boundary was:

$$\dot{P} \approx 7.9 \times 10^{-13} \left(\frac{P}{1 \text{ sec}} \right)^{-11/15}. \quad (1.4)$$

The fact that this *boundary of quiescence* neatly separated members of the 1995 version of the Princeton Pulsar Catalog (Taylor et al. 1993) from the small family of purportedly radio-quiet magnetars (i.e. AXPs and SGRs), was an enticing piece of support for the proposition. Yet this concept pre-dated results from the new Parkes Multi-Beam survey [<http://www.atnf.csiro.au/~pulsar/psr/pmsurv/pmw/>] that has

discovered a small number of pulsars of higher magnetization than previously known (e.g. Camilo et al. 2000), with three lying above this putative quiescence boundary (BH01). This development proves not to be unduly disturbing, since only a small change in the emission altitude can comfortably accommodate the new detections (BH01). Moreover, the “polarity” of the rotating magnetosphere can influence the nature of the acceleration gap, with significant consequences for the boundary of quiescence (Zhang & Harding 2000b). What is more telling, from an observational perspective, is that one of the radio pulsars recently discovered in the Parkes Multi-Beam Survey, PSR J1814-1744, lies very close to the anomalous X-ray (AXP) pulsar CTB 109, so that a single radio quiescence line cannot separate the radio pulsar and AXP/magnetar populations. This proximity coupled with the fact that PSR J1814-1744 has not been detected in X-rays (Pivovaroff, Kaspi & Camilo 2000) strongly suggests that a quantity other than P and B_0 has a profound influence on the properties of highly-magnetized radio pulsars and AXPs.

From a theoretical standpoint, the suppression of pair creation at high fields by photon splitting is not unequivocal. The extensive investigation by Baring & Harding (2001) of photon propagation and attenuation in general relativistic magnetospheres revealed that suppression was significant only if both polarization states (in the external magnetic field) of photons could split, rather than just one. This point addresses a subtlety of QED dispersion of the magnetized vacuum, principally in relation to selection rules derived by Adler (1971): only one polarization state is amenable to splitting in the limit of weak to moderate vacuum dispersion. While almost certainly applicable to typical pulsars, this contention, based on the leading order contribution to the dispersive properties provided by the vacuum, may or may not persist in supercritical ($B \gtrsim 4.41 \times 10^{13}$ Gauss) fields where higher order QED corrections become operative. Hence, whether or not splitting can act to inhibit pair creation critically depends on this unanswered question of physics, the mathematical solution of which is potentially difficult or intractable.

Off-Beam Pulsars. The situation concerning on-beam pulsars motivates an expansion of perspective. From the foregoing discussions, EGRET-type pulsars typically have spectra flatter than EGRET UIDs, and high field counterparts might match the UID slopes if a conspiracy establishes their turnovers at just the right energies to mimic the steeper UID spectra. In the absence of a comfortable explanation of UIDs within the context of on-beam polar cap pulsars, Harding & Zhang (2001) recently proposed *off-beam* pulsars as candidates for some UIDs with Gould Belt associations. Effectively, the line of sight to Earth

does not cut the rim of the polar cap in these sources, but rather samples a broader (spatial) wing corresponding to higher altitudes above the neutron star surface, from which the emission is typically at lower energies, but with a harder spectrum. The hardness originates in the curvature primary photons, with a simultaneous drop in the maximum energy due to the combination of pair creation attenuation and field geometry. The net effect is that the spectrum in the EGRET band is steeper for these sources, due to the influence of a cutoff in the near-GeV range, however the solid angle of emission increases from that of on-beam pulsars. Hence, pulsation searches will be biased towards on-beam pulsars despite off-beam ones constituting a larger percentage of the population. While an attractive proposition in several ways, this suggestion still mandates some fine-tuning of the observational perspective to generate spectra that match UID observations. This issue plagues the high-field pulsar explanation also, and in fact, these two alternatives pose a challenge: how can one discriminate between off-beam/moderate B and on-beam/high B scenarios given that they display similar spectral properties. The answer may be provided by population statistics.

4. GLOBAL PROPERTIES FOR POPULATION STUDIES

Gamma-Ray Luminosities. As indicated in the Introduction, one of the principal successes of the polar cap model is its prediction (Harding 1981) of an almost linear correlation between the inferred luminosity of gamma-ray pulsars and B_0/P^2 , i.e. the voltage across the open field lines for standard polar caps. This correlation, while not exact, largely due to the uncertainty in determining source distance by folding (radio) dispersion measures into the Taylor-Cordes (1993) galactic electron model, is distinctly different from the canonical spin-down luminosity, $\propto B_0^2/P^4$, which is mirrored by the X-ray pulsar population (Becker & Trümper 1997). An enticing feature of this prediction was that only 2 gamma-ray pulsars were known at the time it was proposed, and subsequent predictions by competing analyses/models (e.g. Sturmer & Dermer 1994; Romani & Yadigaroglu 1995; Cheng & Zhang 1998; Rudak & Dyks 1999) and revisions (Zhang & Harding 2000a) all post-dated the EGRET database. The current status is that the polar cap expectations (Sturmer & Dermer 1994; Zhang & Harding 2000a) match the data more accurately than their outer gap counterparts (Romani & Yadigaroglu 1995; Cheng & Zhang 1998), with each group of researchers offering different B_0 and P dependences for the luminosity (see Harding 2001a for a review). To some extent, this situation is limited by

small number statistics, an issue that will be irrelevant in the GLAST era, when such correlations will be established on a really firm basis.

Setting aside partisan theoretical justifications, this observational correlation motivates a revision of historical thinking. Traditionally, the EGRET community has used the spin-down luminosity B_0^2/P^4 as an indicator of a pulsar's observability. While theoretically motivated in some sense, this choice does not match the established trend, and can dictate periods that are selected in pulsation searches. While this has netted most pulsars high up on a $B_0^2/P^4/d_{\text{PSR}}^2$ rank-ordered list (where d_{PSR} is the pulsar distance), certain gamma-ray pulsars (notably the longer period pulsars PSR 0656+14 and PSR 1055-52) are surprisingly low in spin-down luminosity, and millisecond pulsars have proven extraordinarily difficult to detect (up till PSR 0218+4232, see Kuiper et al. 2000) given their short periods. Clearly, a gamma-ray luminosity dependence $L_\gamma(P, \dot{P})$ that differs from the spin-down one will dramatically modify the observability criterion, particularly if the period dependence is substantially different. Furthermore, the spectral shape also influences the observability (Baring & Harding 2000), a more subtle influence. This is a consequence of how the luminosity is distributed in the gamma-ray band, specifically that portion that emerges above the threshold sensitivity for a specific gamma-ray detector. The driving parameters for such an apportionment are ε_{MAX} , index α_n , and to a lesser extent ε_{MIN} , since the spectra are generally flat enough for the bulk of the luminosity to emerge at the highest energies. These parameters control the normalization of the pulsar gamma-ray power-law.

An appropriate definition of a detector's observability $\mathcal{O}(\varepsilon_{\text{TH}})$ is the *integral* flux above an effective instrumental energy threshold ε_{TH} . For pulsars with $\varepsilon_{\text{MIN}} \ll \varepsilon_{\text{TH}}$, the usual case for GLAST considerations, this scales as the luminosity divided by the spectral normalization, yielding $\mathcal{O}(\varepsilon_{\text{TH}}) \propto L_\gamma(P, \dot{P}) \varepsilon_{\text{MAX}}^{(\alpha_n-2)} / d_{\text{PSR}}^2$ (Baring & Harding 2000). Modifications to this dependence are possible, in particular if $\varepsilon_{\text{MIN}} \gtrsim \varepsilon_{\text{TH}}$, in which case $\mathcal{O}(\varepsilon_{\text{TH}}) \propto L_\gamma(P, \dot{P}) / \varepsilon_{\text{MIN}} / d_{\text{PSR}}^2$. Either of these possibilities yields substantially different observabilities from the spin-down formula, assuming that ε_{MAX} and ε_{MIN} scale with B_0 and P approximately as the low field alternative offered in Eq. (1.3). This leads to the conclusion that observabilities predicted for GLAST pulsation searches should follow a dependence somewhere in between B_0/P^2 and $B_0^2/P^{5/2}$. Using the latter possibility, Baring & Harding (2000) generated a revised rank-ordered listing that indicated a dramatic rearrangement from the traditional EGRET ordering. Notable changes included the much higher ranking of the “outlier” longer period gamma-ray pulsars PSR 0656+14 and PSR 1055-52, and the marked lowering of millisecond pulsars (PSR

1939+2134, PSR 0437-4715, PSR 1744-1134, etc.) in the ranks, specifically out of the top 40. Both of these reflect the weaker dependence of the revised observability on P . The old and new rankings are listed in Table 1 for the confirmed and candidate (non-millisecond) gamma-ray pulsars; it becomes clear that such revisions mute questions of why PSR 1055-52 was seen by EGRET. Refinements of such rank orderings are in progress, an interesting preparatory step for the GLAST mission.

Table 1 CGRO Gamma-Ray Pulsars and rank-ordered listings

PSR	P (sec)	\dot{P}	$B_0^2/P^4/d_{\text{PSR}}^2$ rank	$B_0^2/P^{5/2}/d_{\text{PSR}}^2$ rank
Vela	0.089	1.25×10^{-13}	2	1
Crab	0.033	4.21×10^{-13}	1	2
Geminga	0.237	1.1×10^{-14}	4	3
1509-58	0.150	1.5×10^{-12}	5	5
1706-44	0.102	9.3×10^{-14}	7	6
0656+14	0.385	5.5×10^{-14}	20	13
1951+32	0.040	5.85×10^{-15}	6	14
1055-52	0.197	5.83×10^{-15}	33	23

Gamma-Ray vs. Radio Observability. Pulsation searches for EGRET UIDs that have spatial associations with known radio pulsars naturally bias the search phase space in P and \dot{P} . Yet there is no guarantee that every gamma-ray pulsar (or EGRET UID) is a radio pulsar, and vice versa. The polar cap and outer gap models make distinctly different predictions of the correlation between observing gamma-ray and radio emission from pulsars, based largely on assumed emission region geometries. Outer gap models (e.g. Romani & Yadigaroglu 1995; Zhang et al. 2000) suggest an almost complete disconnect between emission in the two wavebands so that detected (normal as opposed to high B) gamma-ray pulsars should mostly be radio-quiet due to the much larger solid angle in the gamma-ray beam. The fact that Geminga is the only radio-quiet gamma-ray pulsar may be bothersome to outer gap proponents. Perhaps more disconcerting is that the best determinations of altitudes for the radio emission (e.g. Gil & Han 1996) may suggest more of a connection with polar caps than outer gaps. Even if the origin of both radio and gamma-ray emission is connected to pair creation in a polar cap, the solid angles of these components should be somewhat different. There are large uncertainties present in any prediction of the ratio

of numbers of gamma-ray and radio pulsars, since models must incorporate details of the distribution of fields and periods at birth, the spatial and velocity distributions of pulsars in the galaxy, the influence of galactic gravitational potentials, and luminosity and solid angle geometry prescriptions for both the gamma-ray and radio emission. Assembling such ingredients, both Sturmer and Dermer (1996) and the very recent analysis of Gonthier et al. (2001) find that only a minority of EGRET pulsars would be expected to be radio-quiet. This fraction increases substantially for GLAST to an almost 50/50 radio-quiet/radio-loud situation according to Gonthier et al. (2001); this result is a consequence of GLAST's improved sensitivity enabling it to sample deeper than typical radio surveys. Hence blind pulsation searches shall be a much more salient tool for GLAST, and the gamma-ray UID community may well have to forgo attachments to radio pulsar counterparts.

5. CONCLUSION

This review has detailed some of the expectations for polar cap pulsar properties that will prove extremely useful subsequent to pulsar identification for gamma-ray sources. These include spectral trends with B_0 and P , identifying the science gains to be made given a considerable gamma-ray pulsar database in the GLAST era. Yet the discussion has also elucidated possible guidelines for UID pulsation searches so that pulsar science is not merely a *post-facto* consideration for the identification process. It is clear that standard gamma-ray pulsars like the Crab, Geminga and Vela might not constitute the majority of the subset of UIDs that eventually turn out to be pulsars, at least if the mean GLAST gamma-ray source characteristics are similar to those of the EGRET UIDs. Turning to off-beam pulsars or highly-magnetized on-beam ones as candidates does not dramatically change the search phase space (P and \dot{P}) from current agendas. Lowering the instrumental threshold energy as much as possible is a worthwhile goal, provided that it does not compromise threshold sensitivity and angular resolution properties. While it has been argued that observability criteria need revision from historical preferences, and that there is probably less need to be biased against searching at longer periods, since magnetars appear to be unlikely candidates for UIDs, there is no compelling reason to search on supersecond periods and in the domain $\dot{P} \gtrsim 3 \times 10^{-12}$ sec/sec. Continued identification efforts with the EGRET database and refinements to theoretical models in the next half decade will help set the stage for the watershed of gamma-ray identifications to be attained by GLAST.

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